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# Upper-Atmosphere-Density Determination Using NRL Artificial Satellites

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## ABSTRACT

NRL has had several artificial satellites placed in orbit for various experimental purposes. By observing the changes in orbital elements, it has been possible to calculate the density at the altitude range of 950 to 1160 km for the past 3 years. Long- and short-term effects are noted and discussed. A cyclical variation of 27 days has been found. It is apparently due to the variation in solar activity with the sun's rotation. The centers of activity appear to be stationary on the sun's surface for months at a time.

## PROBLEM STATUS

This is an interim report; work is continuing.

## AUTHORIZATION

NRL Problem R04-16
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## UPPER-ATMOSPHERE-DENSITY DETERMINATION USING NRL ARTIFICIAL SATELLITES

NRL has had several satellites placed in orbit for various experimental purposes. As a part of the development of the Space Surveillance System (1), several smooth spheres have been launched. Observations of these objects were used to determine the system coverage. Two identically appearing spheres, having a 10:1 ratio in masses, formed the basis for the Dual Calsphere experiment (2). The changes in semimajor orbital axis of these two spheres were recorded to calculate the relative drag effects of the two objects. The rate of change of the semimajor axis was seen to vary, even in the few weeks' time. It appeared that extended observations of the lighter calsphere should provide upper-atmosphere-density data for as long a period as one wished to observe.

With this in mind along with the need for a large target satellite for Space Surveillance System calibration, NRL built and arranged for the launch of two dodecapole reflectors. Each object is a 26-cm sphere with 12 hollow rods erected normal to the faces of an equivalent regular dodecahedron. Each rod is 1.27 cm in diameter and 7.62 m long. A photograph of the object with rods not extended is included as Fig. 1. These satellites serve several purposes. To the 217-mHz, bistatic cw radar of the Space Surveillance

Fig. 1 - Dodecapole satellite (prelaunch) with the 12 rods in stowed position

System, they are large targets. For the same reasons, they are useful as passive communication reflectors. Finally, the mass-to-area ratio and the nearly isotropic projected area make them useful objects for determining drag due to the atmosphere at the 1000-km altitude.

These objects and the facilities of the Space Surveillance System make data available for a region of the upper atmosphere that is otherwise poorly covered. Little photographic work is done on objects at this height.

As a part of its regular task, the Space Surveillance System prepares five-card orbital elements on over a thousand orbiting objects. Current observations are used in a differential correction program to update the elements. The semimajor axis is calculated to the eighth decimal place in terms of the earth's radius. In the appendix, the change in semimajor axis is related to the density of the medium in which the satellite moves.

Table 1
Excerpt from Log of Significant Data on Object 900 (Calsphere) and Object 1310 (Dodecapole)

| Date (Modified Julian Days) | Date (Calendar) | Semimajor Axis (Earth Radii) | |
|---|---|---|---|
| | | Object 900 | Object 1310 |
| 39959 | Apr. 13, 1968 | 1.16717726 | 1.14241144 |
| 39966 | Apr. 20, 1968 | 1.16717258 | 1.14238240 |
| 39973 | Apr. 27, 1968 | 1.16716880 | 1.14235698 |

The log is continuous from January 1966 to date. The elements, with epoch at the last south-to-north equator crossing on Friday, are received at NRL each Monday morning. The density values for each week are plotted in Fig. 2 and connected by segments of straight lines. The smooth curve joins points representing the mean value of each week and the two before and the two after. These 5-week running times tend to obscure short-term variations, 1 month or less, but point up the longer period trends. The lower plot is for satellite 1964-63C, the lighter sphere used in the Dual Calsphere experiment. The upper plot is for 1965-16G, one of the dodecapoles.

The weekly changes in semimajor axis are shown in Fig. 3 for three different satellites. Both dodecapoles and the light calsphere are shown here with a logarithmic scale. The purpose is to show the close time correlation of the accelerations of the three objects. The plot shows that the ratios of the maximum-to-minimum acceleration of the sphere and dodecapole at nearly the same height are approximately equal. The dodecapole at lower altitude shows a somewhat greater ratio.

Looking at Fig. 2, it is apparent that the air density, as derived from acceleration, has shown marked changes during the last 2-1/2 years. Added to the general increase are at least two apparently periodic functions. The weekly data points show 13 maximum values during 1967. The mean period is approximately 27 days. This interval is close to the sun's synodic rotation period and also the moon's period. The smooth curves show maximum values some 10 months apart. Note that the short-term variation has maximum amplitude at the 10-month maximum times. This observation tends to eliminate the influence of the moon, which if significant, would be constant except for a small interaction with the sun. The 27-day variation, then, must be attributed to solar activity, varying with rotation.

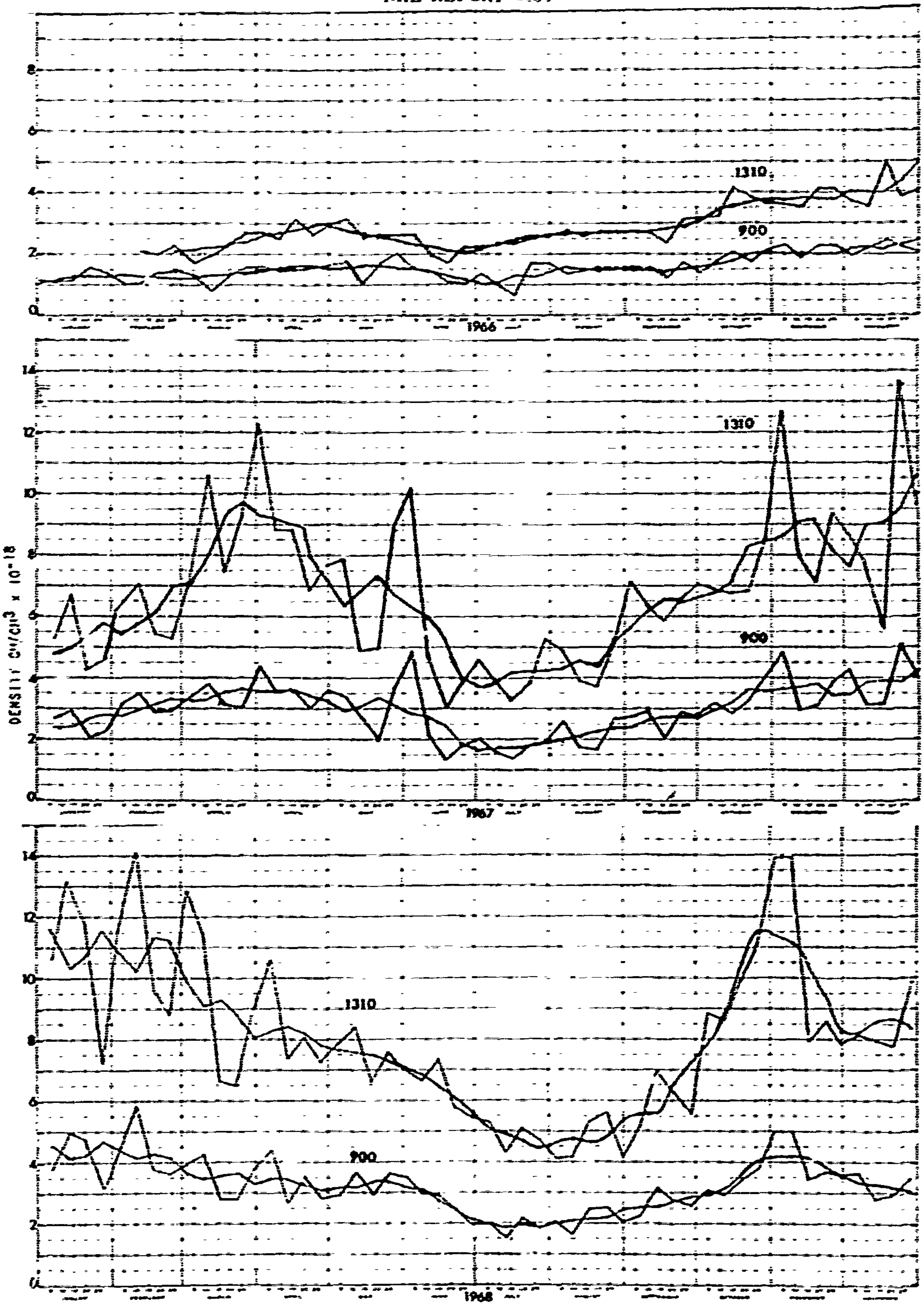


Fig. 2 - Density of the upper atmosphere versus time

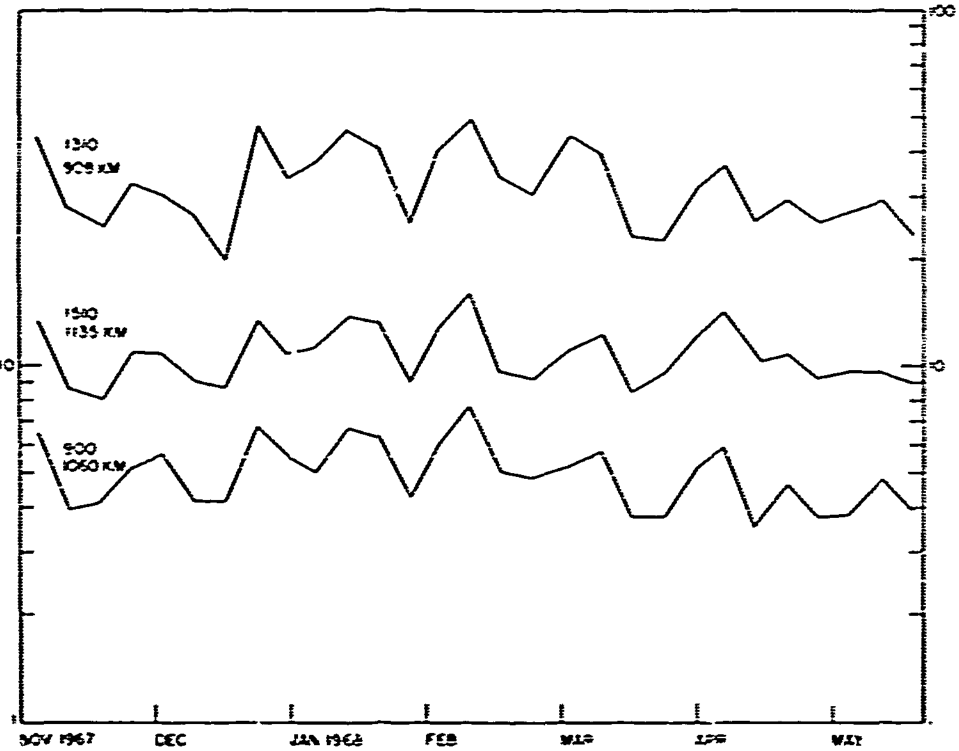


Fig. 3 - Changes in semimajor axes of three satellites versus time

The variation is consistent with the effect of a source of solar activity — stationary on the sun's surface and varying in intensity over a period of months. The activity appears to persist through the changing pattern of sun spots.

At this time, November 1968, accelerations are high, indicating the third such period of maximum activity since the start of the study. The apparent 10-month period is supported by these three maxima, but further observation will be necessary before any firm inference can be drawn.

All calculations made to this point are based on the assumption that each weekly decrement in the semimajor axis reflects a constant or slowly changing drag during that period. Some variations must be considered to see if the assumption is justified. The effective density of the upper atmosphere is a function of the temperature resulting from solar excitation. During this study each satellite has been subject to various geometrical arrangements with respect to the earth and sun. At times, each object was in sunlight throughout the orbit. At other times they had varying times of immersion in the earth's shadow. At times the plane of the orbit included the diurnal solar bulge. Since the observations cover more than 2 years, seasonal variation in sun-to-earth distance must be considered.

If the earth-sun line is nearly perpendicular to the plane of the orbit, the satellite will move through a medium that is uniformly excited by the sun. At the altitude of these satellites the surface temperature variations have little effect on the atmospheric temperature. As the plane of the orbit moves to include the sun's position, the satellite encounters regions of different excitation including some full shadow. If the integrated

effect of the drag around the whole orbit varies as a function of the apparent solar position, then a periodic effect should be noted. Since the rotation of the plane of a near polar orbit (satellite 900) is only a few degrees per year, the effective period of any variation due to solar position should be nearly 1 year.

Due to the economic problem of getting satellites launched as cheaply as possible, NRL has taken advantage of excess lift capability of certain primary payload operations, even though the orbital parameters might not be exactly those desired. The dodecapole, object 1310, was placed in an orbit with a nominal 70-degree inclination. In this case, the result is good. The orbital plane revolves through 360 degrees in approximately 4 months as compared with the 12-month period of the calsphere (900). The close agreement of the accelerations of the two bodies shows that the effect due to solar position is small or negligible compared with that due to changes in solar radiation.

Artificial satellites of known size and mass, isotropic drag, and circular orbits used in conjunction with current orbital element determinations can provide good measurement of the density of the outer atmosphere. The objects used in this study are well fitted for the altitude near 1000 km. The accelerations are high enough to measure easily and low enough that data may be obtained over an extended period of time.

At a lower altitude these objects would decay so rapidly that they could show only short-term effects. This points up the need of some future launches of spherical bodies with greater mass-to-area ratio for lower altitude studies.

An object with higher drag could be used with a daily element updating program to make a more detailed study of short-term variations that is possible with the present weekly reports.

This NRL study will be continued through the coming period of higher solar activity and as long thereafter as the data are significant.

## REFERENCES

1. Easton, R.L., and Fleming, J.J., "The Navy Space Surveillance System," Proc. I.R.E. 48:663-669 (1960)

2. Zirm, R.R., Brescia, R.E., and Rovinski, R.S., "The Dual Calsphere Experiment," NRL Report 6271, July 1965

## Appendix

# ATMOSPHERIC DENSITY AT 600 NAUT MI AS DETERMINED BY THE CHANGE OF ORBITAL OF SATELLITE 900, ONE OF NRL CALSPHERES

The density of the upper atmosphere has been calculated in several studies from observations of satellites. There is a direct relationship between the decay of a satellite orbit and the air density. In general, the rate of change of the semimajor axis of an object in orbit about the earth is proportional to the density of the atmosphere through which it moves:[*]

$$\frac{da}{dt} = -\frac{2e\sin V}{n\sqrt{1-e^2}}\,\frac{\rho C_D A V V_\oplus e\sin V}{2m\sqrt{1+e^2-2e\cos V}}$$

$$-\frac{2a\sqrt{1-e^2}}{nr}\,\frac{\rho C_D A V}{2m}\left[\frac{V_\oplus(1-e\cos V)}{\sqrt{1+e^2-2e\cos V}} - V_a\cos\beta\right]. \quad \text{(A1)}$$

where $e$ = eccentricity. Before defining the other elements in the equation, we simplify it by setting $e = 0$; therefore,

$$\frac{da}{dt} = \frac{-2a\rho C_D A}{2nrm}\,V(V_\oplus - V_a\cos\beta)\,. \quad \text{(A2)}$$

where

$V$ = velocity of the satellite with respect to the atmosphere,

$V_\oplus$ = velocity of the satellite with respect to inertial space,

$V_a$ = velocity of the atmosphere with respect to inertial space, and

$\beta$ = angle between $V_a$ and the plane of the orbit.

Assume $\beta$ = 90 degrees for $e = 0$ and $a = r$; therefore,

$$\frac{da}{dt} = -\frac{\rho C_D A}{nm}\,V V_\oplus\,. \quad \text{(A3)}$$

where

$\rho$ = atmospheric density,

$C_D$ = ballistic coefficient,

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[*]R. W. Wolverton, editor, "Flight Performance Handbook for Orbital Operations," New York:Wiley, 1963.

$A$ = projected area,

$n$ = angular velocity, and

$m$ = mass of satellite.

All of these parameters are easily defined except for the ballistic coefficient $C_D$. In the early years of upper atmosphere research, the value 2.0 was assumed. According to a recent study* the value for an oxide-coated sphere in the altitude range where helium is the principal component of the atmosphere lies in the range 2.4 to 2.6. For a polar orbit $V = V_a$; therefore,

$$\dot{a} = \frac{\rho A C_D V^2}{mn},$$

where

$$V^2 = V_e^2 / a,$$

in which $V_e$ = circular orbital velocity at the surface of the earth = 7.205 km/sec and

$$1/n = a^{3/2}\, 5069/2\pi .$$

Therefore,

$$\frac{\dot{a}R}{7(86400)} = \frac{\rho A C_D V_e^2 a^{3/2}\, 5069}{m a 2\pi},$$

$$\rho = \frac{m\dot{a}R 2\pi}{AC_D 7(86400)(7.905)^2(10)^{10} a^{1/2}\, 5069}$$

$$\rho = \frac{m(2\pi)(6.37\times10)^8 \dot{a}}{AC_D 7(86400)(7.905)^2(10)^{10}(5069) a^{1/2}},$$

and

$$\rho = \frac{m\dot{a}}{AC_D a^{1/2}}\, 2.09(10)^{-12}\ \mathrm{g/cm^3}$$

The various numbers in the above conversion give a formula that accepts the quantities $a$ and $\dot{a}$ in earth radii and earth radii per week, respectively. In this study, the value of the semimajor axis is noted each week, and the difference between successive readings is taken as the mean rate for the week.

*G. E. Cook, "Drag Coefficients of Spherical Satellites," RAE TR 65218, Oct. 1965.

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